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k_t-factorization in a variable-flavor-number scheme: heavy-hadron production

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We present a comprehensive study of heavy-hadron production, including D and B mesons, heavy baryons, and the B_c meson. Our calculations are based on the k_t-factorization, implemented within a variable-flavor-number scheme, as initiated in Ref. [1]. The present work completes the initial study by including the scale dependence of fragmentation functions, with a special emphasis on the gluon-to-heavy-hadron contribution.

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The high-energy factorization (HEF) [2–5], also known as k_t-factorization, was initially designed to resum large $\log(1/x)$. This formalism is sometimes related to the correlation limit of the Color-Glass-Condensate effective theory[1], for instance, in [9]. The proton-proton to parton differential cross section reads

$$\frac{d\sigma(pp \to j+X)}{dy d^2 p_t}(y, p_t; \mu_f) = \sum_{a,b} \int dy_4 \int_0^{k_{\max}^2} dk_{1t}^2 dk_{2t}^2 F_a(x_1, k_{1t}; \mu_i) \times F_b(x_2, k_{2t}; \mu_i) d\hat{\sigma}_{ab\to j+X}(x_1, x_2, p_t, k_{1t}, k_{2t}; \mu_i, \mu_f), \quad (1)$$

The variables x_1, x_2, k_{1t}, and k_{2t} are the longitudinal momentum fractions and transverse momenta carried by the initial partons. The parton j has rapidity y and transverse momentum p_t, and there is an integration on y_4, the rapidity of the second outgoing parton. The variables μ_i and μ_f are the factorization and fragmentation scales, respectively, and $d\hat{\sigma}_{ab\to j+X}$ is the differential off-shell partonic cross section.

A central ingredient is the unintegrated PDFs (UPDFs) F_a, carrying information on both the longitudinal and transverse momentum of the parton. Older studies, designed for asymptotic energies, focused on the gluon distribution. However, LHC energies are not large enough to neglect the role of the quark, and in [1], we undertake the implementation of the HEF in a variable-flavor-number scheme (VFNS). In this case, the indices a and b in Eq. (1) refers to both gluon and (heavy) quarks. It is known that the VFNS should be preferred to a fixed-flavor-number scheme (FFNS) for observables measured as a function of the hadron transverse momentum P_t, in particular at leading order. Nowadays, most of the collinear PDFs, used to build our UPDFs are extracted in a VFNS, which is another reason why the implementation of the HEF within this scheme was urgent.

Our UPDFs are built following a slightly modified KMRW procedure [10, 11], and obey approximately [2]

$$x f_a(x; \mu) = \int_0^{\mu^2} F_a(x, k_t^2; \mu) dk_t^2, \quad (2)$$

where f_a are the collinear PDFs. We use them as input to the event generator KaTie [13], employed to compute Eq. (1) at leading order, and, in agreement with the discussion in Ref. [14], we choose $k_{\max}$ to be of the order of the hard scale $Q \sim p_t$. At this order, the off-shell cross section in Eq. (1) is independent of the scales μ_i and μ_f. In Ref. [1], the fragmentation function was also scale independent. The main objective of the recent work [15] was to implement this dependence and to study the new contribution $D_{g\to H_Q}(z; \mu_f)$ arising from the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution [16–18]. The heavy-hadron cross section is obtained by a convolution of Eq. (1) with the fragmentation functions (FFs)

$$\frac{d\sigma(pp \to H_Q+X)}{dY d^2 P_t}(Y, P_t) = \sum_j \int_{z_{\min}}^1 \frac{dz}{z^2} D_{j\to H_Q}(z; \mu_f) \frac{d\sigma(pp\to j+X)}{dy d^2 p_t}\left(y, \frac{P_t}{z}; \mu_f\right), \quad (3)$$

[1] See Refs. [6–8] for a review on this formalism.
[2] See Refs. [1, 12] for more details on this point.

where, Y and P_t are the rapidity and transverse momentum associated with the heavy hadron H_Q. Due to our finite-order calculations, the heavy-hadron cross section retains a dependence on μ_i and μ_f leading to the usual scale uncertainties. Our default choice is

$$\mu_i = m_t = \sqrt{m_Q^2 + p_t^2}, \quad \mu_f = \sqrt{M^2 + P_t^2} = M_t, \tag{4}$$

with m_Q and M the heavy-quark and hadron mass, respectively.

1. Fragmentation functions

Our earlier work [1] focused exclusively on cases where the parton j of Eq. (3) is a charm or bottom quark. However, it receives contributions from the fragmentation of light flavors to heavy hadrons when $\mu_f > \mu_0$, with μ_0 the initial scale for the (timelike) DGLAP evolution. In this study, we include the gluonic term $D_{g\to H_Q}$. The role of other light flavors is generally negligible. The DGLAP evolution of our fragmentation functions is performed using QCDNUM [19], with the initial scale fixed at $\mu_0 = m_Q$.

The initial condition for $D_{Q\to H_Q}(z;\mu_0)$[3] is given by the Peterson's parametrization, requiring two inputs: the fragmentation fraction $f(Q \to H_Q)$ and the free parameter ϵ_Q. We summarize in table 1 the values used in this paper.

Hadron	Fragmentation fraction	Parameter ϵ
D^0	0.588	0.008
B^+	0.403	0.001
Λ_c^+	0.1	0.001
Ξ_c^0	0.0595	0.001

Table 1: List of parameters corresponding to Fig. 1.

2. Results

Using the scales of Eq. (3) and a procedure similar to the SACOT scheme (see Ref. [15] for more details), we present in Fig. 1 a sample of our results for D and B mesons, as well as for charmed baryons. We show in pink, blue, and black the $g \to H_Q$, $Q \to H_Q$, and total contribution, respectively. Here, g and Q refer to the parton produced in the partonic scattering, and convoluted with the appropriate fragmentation functions. In all cases, the gluon-to-heavy-hadron contribution is fairly negligible at intermediate and large P_t, but is comparable to the heavy-quark contribution at small P_t. This last property improves the agreement between our central values and experimental data. In the top-right figure, the color bands correspond to our evaluation of scale uncertainties. These are summed in quadrature, leading to the gray color bands in bottom figures. Note also the

[3] $D_{g\to H_Q}(z;\mu_0) = 0$.

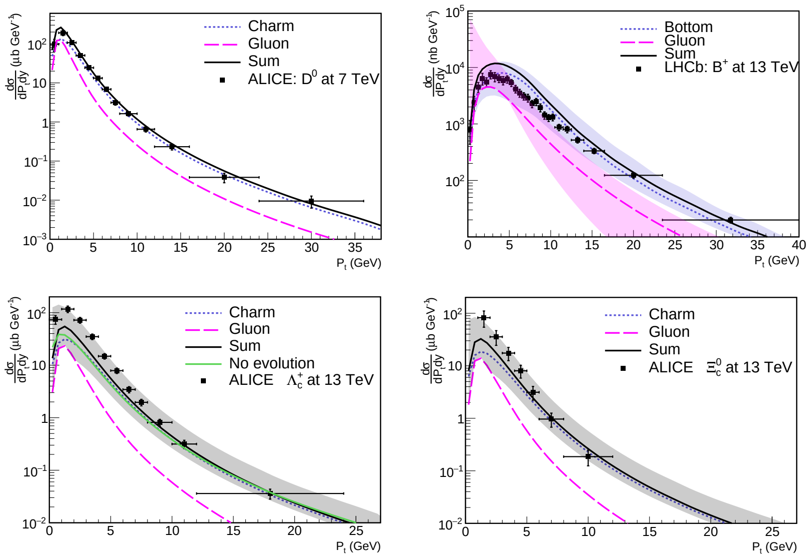

Figure 1: Theoretical results compared to ALICE [20–22] and LHCb data [23].

green line in the bottom-left figure, allowing a comparison between the case with evolved fragmentation functions, in black, and without (non-perturbative parameters should be adequately modified).

While in agreement within uncertainties, we observe an underestimation of baryon data by our central values. This is a general feature, also true with collinear factorization calculations, and probably related to a different mechanism enhancing heavy-baryon production at small P_t.

3. Conclusion

The main goal of the present work was to complete our k_t-factorization calculations [1] with scale-dependent fragmentation functions. The DGLAP evolution makes the gluon-to-heavy-hadron contribution non-zero, improving the description of data at small P_t. We worked within a variable-flavor-number scheme and demonstrated the capability of this formalism to describe a wide range of heavy-flavor observables. This is achieved with a single consistent choice for the factorization and fragmentation scales, μ_i and μ_f. While in agreement within uncertainties, we observe an underestimation of baryon data by our central values. This is a general feature, also true with collinear factorization calculations, and related to the heavy-baryon enhancement.

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